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CAPABILITIES OF SMALL STATURE WOMEN TO PERFORM OPERATIONAL FLIGHT TASKS DURING G-STRESS

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BACKGROUND

With expansion of the role of women in military combat operations, including those in the fifth percentile for weight, i.e., 120 (54.4 kg) pounds or less, it is essential to determine if such individuals can perform certain tasks under dynamic conditions given their small stature. In particular, this study addresses whether these females possess the upper body muscular endurance to perform high performance flight maneuvers such as those experienced in training, air combat and during emergency flight conditions. The ability to eject and support added head weight, as required by the use of helmet mounted devices, is also determined.

In general, measures of female mean strength are comparable to males for lower extremity static efforts and various dynamic lifting, pushing and pulling activities (5). Due to a smaller muscle moment arm, women appear to have more difficulty performing muscular exertions involving flexion, abduction and rotation of the arm about the shoulder relative to men. According to Chaffin and Andersson (5), gender differences reported in population strength data are almost entirely explained by differences in muscle size as estimated by lean (fat-free) body weight or limb cross-sectional area (circumference measurements) dimensions. If a man and woman with similar fat-free body weight are trained to the same degree, their isometric muscle strength performances will probably be equal (5). And despite the obvious differences in muscle mass between males and females, gross anthropometric descriptors alone are not well correlated enough with strength to be of practical value. Caldwell (4) stated that, "While arm strength may be related to arm dimensions, stature and weight, endurance is not."

While the muscular strength of average stature and weight females should be sufficient to perform high performance flight tasks, females in the 5th percentile may not have that ability. For example, a survey of female isometric strength included seated arm pulls which were similar to that required during ejection (6,11), that is, exerting a 60 lb. pull on a "D" shaped ring. For a seated one handed pull with "D" ring positioned 45 cm above platform just forward of the seat and in the centerline of seat, mean force for the population was 50.9 ± 20.1 lb. (5th percentile mean force = 22.8 lb.) and peak force for the population was 59.7 ± 22.3 lb. (5th percentile peak force = 28.6 lb.). Laubach (10), found that even though flight related upper body exertions should be within average female muscular abilities, small stature and weight females may not be able to generate sufficient muscular force in all planes of motion. Overall, female upper extremity strength was found to be 35 to 79% of men's (mean 55.8%); female lower extremity strength was 57 to 86% of men's (mean 71.9%); female trunk strength was 37 to 70% of men's (mean 63.8%); and with reference to dynamic strength indicators, females were 59 to 84% as strong as males (mean 68.6%).

Note that while strength assessments often require subjects to exert maximal forces during operational settings, a maximal effort is rarely required and strength data may not be "fully relevant" when applied to a particular scenario. Kroemer (9) stated that "as soon as it has been established that the operator's force capacity meets or exceeds the force requirement, strength ceases to be a relevant criterion."

Muscular strength and endurance requirements for various critical tasks performed in USN fixed wing aircraft were assessed based on a survey of aircraft model managers conducted by the Naval Aerospace Medical Research Laboratory in 1994. A synopsis of their responses can be found in reference 12. Overall, the model managers indicated that for high performance aircraft, brute strength was not a major requirement. The most critical muscular strength issue was the need for sufficient muscular endurance, particularly during high-G maneuvers.

OBJECTIVES and SCOPE

The objectives of this study were to determine the ability of small stature females to:

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- Perform upper body muscular tasks associated with fighter aircraft seat ejections under static, worst case acceleration environments (+Gz, inverted, lateral G and flat spin conditions) and during simulated flight conditions.
- Support up to 5 pounds of added head weight under acceleration vectors experienced during catapult, arrestment, and aerial combat maneuvers.
- Perform upper body muscular endurance tasks associated with standard fighter pilot training, aerial combat maneuvers, and in-flight failure modes.

The intent of this study was to determine the range of dynamic strength capabilities of small stature females and any limitations they might have that would impair their ability to accomplish high performance aircraft tasks. In particular, the focus was on those tasks encountered in a "fly-by-wire" aircraft. As such, generalization of these results to flight performance in aircraft employing mechanical controls which require greater muscular strength should be done with great caution. Subjects were deliberately selected to represent the worst case in terms of size and experience to determine what, if any, modifications to hardware or training programs would be required to accommodate this population.

METHODS

Six small stature (defined as ≤ 120 lb. (54.5 kg)) women (32.9 ± 2.9 yr.) participated in this study. Mean anthropometric descriptions were: weight: 51.3 ± 2.8 kg; height: 156.2 ± 5.0 cm; functional leg length: 96.9 ± 2.2 cm; sitting height: 83.3 ± 3.6 cm; sitting eye height: 72.3 ± 3.0 cm; sitting acromial height: 55.6 ± 3.0 cm; thigh clearance: 14.6 ± 0.5 cm; buttock-knee length: 55.4 ± 0.8 cm; sitting abdominal depth: 21.2 ± 1.3 cm; sitting hip breadth: 41.3 ± 2.0 cm; thigh circumference: 53.3 ± 1.4 cm; thumb tip reach: 70.7 ± 2.9 cm; and VO_2 max: 36.7 ± 2.7 ml·kg⁻¹·min⁻¹. By using a push/pull task to measure isometric flexion, extension and lateral neck strength, mean peak neck strengths were: flexion 8.3 ± 1.5 kg.; extension: 11.1 ± 3.4 kg.; right: 7.1 ± 1.8 kg.; left: 7.5 ± 2.3 kg. Due to scheduling problems and equipment size limitations, not all subjects participated in all tasks. Informed consent was obtained from all subjects prior to the conduct of this investigation in accordance with SECNAVINST 3900.39B and all pertinent US Department of Health and Human Services regulations.

These studies were conducted at the Dynamic Flight Simulator (DFS) facility in Warminster, PA, USA. Installed in the DFS gondola was a cockpit which had been determined to have the same dimensions and control layout as in an US Navy fighter/attack aircraft. The flight simulation was driven by Silicon Graphics Incorporated (SGI) equipment and CTA Simulation (Englewood, CO) System's Mission Simulation Software. Three 21" video monitors were mounted in the centrifuge to display out-the-window imagery. The virtual reality visual scene gave the subject a 35° vertical by 120° horizontal field-of-view. The scenery was produced by SGI Reality Engine graphics and was a highly textured database of the Oakland/San Francisco Bay area.

To determine localized upper body muscular fatigue and effort levels, electromyographic (EMG) leads were affixed on the biceps brachii (flexor, BM), brachioradialis (flexor, BRM), triceps (extensor, TM), and deltoid (shoulder abduction, extension, flexion, rotation, DM) muscles (8). Two Ag-AgCl electrodes were placed about 1 cm apart in the middle of the belly of the muscle. The EMG reference electrode was placed on the dorsal side of the forearm over the ulna, an electrically unrelated tissue (2). For the added head weight assessment, EMG electrodes were placed over the sternocleidomastoid (neck flexor, SCM) and the trapezius muscles (neck extensor, TZM) (7). ECG was also monitored and change in heart rate (ΔHR) calculated relative to the rest period immediately prior to G exposure. Subjects wore full flight ensembles with survival vest, torso harness, extended coverage female sized anti-G suit, helmet and positive pressure breathing equipment.

Muscular exertion strength was assessed in the time domain by calculating the EMG root-mean-square (RMS) value. Stronger exertions resulted in higher EMG amplitude. Relative estimates of muscular fatigue were made by determining the EMG frequency content by first passing the waveform through a Hamming Window then calculating the power spectral density (PSD). The frequency content of surface

EMG waveforms decreases (shift to lower components) when a contraction is sustained. This frequency shift can be used to estimate muscle fatigue. Based on a recommendation by Basmajian and DeLuca (2), the characteristic frequency chosen to track was median frequency. Subjects also verbally rated their level of exertion based on the Angel scale (1) and a modified Borg scale (3) was used to estimate subjective fatigue. A summary of test conditions and variables is listed in Table 1.

To perform an ejection, subjects were required to exert a 40 lb. (18.1 kg.) actuation upward pull force on a "D" ring positioned midcenter in front of the ejection seat. Two types of grips were tested under (1) static conditions (1 g), (2) while exposed to various G-loads to simulate "worst case" ejection conditions ("open loop"), and (3) during a DFS flying task. The grips were: two-handed (2-H), in which the subject gripped the ejection handle with the thumb and at least two fingers of each hand; and a one-handed grip (1 H), in which the subject gripped the handle with one hand, then gripped that wrist with the other hand.

For both static and open loop ejections, the grips were randomized and subjects began by placing their hands on the stick and throttle and initiated their pull at a signal from the investigator. During the static ejection pulls, the effect of anti-G suit inflation was determined by pulling the D-ring with the suit either uninflated or inflated to +3 Gz levels (3 psi). Two pulls per hand grip were measured. For the open loop ejection, subjects were exposed to 15 s plateaus (2 s onset and offset times) of +3 Gz, +5 Gz, -1 Gz, -1.5 Gz, +1 Gx, -3 Gx, -5 Gx, and ± 1 Gy in a randomized sequence. The exposure ended after either a successful ejection or 15 s at plateau. Upon a successful pull, a tone sounded, and the subject relaxed. For the dynamic ejection, the subject was in control of the centrifuge. Subjects performed a low altitude (250 to 800 ft), low speed (170 knots) approach toward two different cities. At one mile in front of a tall building in the first city, subjects assumed the correct body position and initiated an ejection (grips were randomized). The time required to execute a successful ejection and the distance traveled during that period were measured. Success in this maneuver was defined as the ability to execute a successful 40 lb. pull prior to crashing into the building. Subjects then climbed to 1,000 ft AGL (above ground level) and flew to the second city, descended, and repeated the sequence using a different grip. They then flew back to the first city and began the sequence again until each of the grip modes was repeated twice during the same insertion.

To simulate the effect of increasing the overall weight of head mounted systems, subjects wore helmets and masks weighing a total of 3.5 (standard configuration), 4.25, or 5.0 lb. (1.6, 1.9, or 2.3 kg.). The additional weight was mounted inside the helmet so that a mass properties analysis indicated that the center of gravity (cg) remained in the same position as in the 3.5 lb. helmet. The higher weights were chosen to determine the envelope in which small stature female necks could support up to 5 lb. under G-stress without injury. Subjects supported their heads so they could read the head-down and head-up displays. To determine the extent of their visual range, targets were positioned on top of the three 21" monitors. Subjects were exposed to rapid onset (2 s rise) G-loads which could be experienced during flight, catapult and arrestment modes (-1 Gz, ± 1 Gy, ± 2 Gx, ± 4 Gx, +2 Gz and +4 Gz). G plateaus lasted up to 20s, or until all targets had been identified or read, or until the run was halted due to discomfort. The ability to accurately read display symbology was also tested by asking the subjects to verbally report the HUD airspeed, heading and altitude readings and identify the quadrant in which an airport was positioned on the center head-down radar display (HDD). To simulate G-loads experienced during an aerial combat engagement, subjects were exposed to a "Gillingham" simulated aerial combat maneuver (Figure 1) and asked to identify targets and read from the various displays at the higher Gz plateaus. During rest periods subjects were asked to fixate on the cockpit console keypad while different values were set for the HUD readings and the airport repositioned in the HDD so subjects could not simply memorize display values.

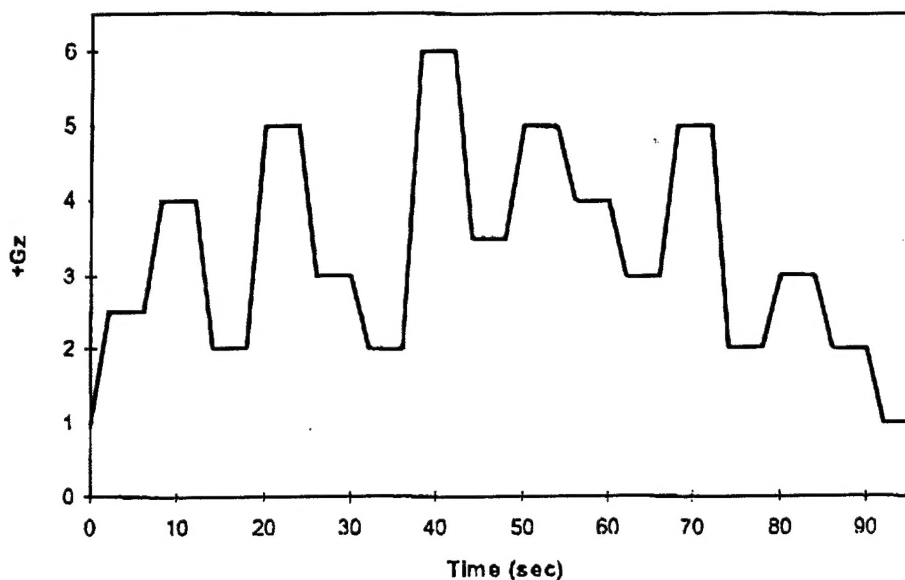


Figure 1. Gillingham Simulated Aerial Combat Maneuver (SACM).

Relative effort of muscular effort for SCM and TZM were assessed by measuring EMG RMS (normalized to the maximum exertion level for each muscle group) and comparing values based on their relative head position and the sequence in which subjects looked at the targets, i.e. first while holding their heads upright ("mid-range," viewing the LED's and HUD); then looking up at the monitor targets ("head-up"); and last looking down at the HDD, landing gear knob and climb rate meter ("head-down"). An ANOVA and Fisher's Least Significant Difference (F-LSD) post hoc test were run to determine differences in muscular effort based on head position and helmet weight. To determine changes in the EMG attributable to muscular fatigue, the change in EMG f_{med} (Δf_{med}) for these positions was also analyzed in a similar fashion.

Performance decrements referable to a decline in muscular endurance are caused by muscular fatigue brought about by long periods of sub-maximal exertions. For example, a pilot may perform a sequence of engagements which feature short duration sustained G turns, followed by unloading the aircraft, regrouping, and pulling G's again. Another demanding task involves a series of bombing runs in which the aircraft dives at greater than +4 Gz, the pilot delivers ordnance, pulls out, then regroups and repeats the sequence as many as two dozen times. Muscular endurance becomes a critical factor during asymmetric flight in which one engine is inoperative and the pilot has to maintain constant back pressure on the control stick (as opposed to the normal 0 lb.) and a sub-maximal load on the rudders to maintain trim.

To simulate these muscular endurance tasks, subjects were trained in the DFS to perform simulated bombing runs, a SAM (surface to air missile) avoidance pattern, and an engine-out scenario with landing tasks. During initial training, subjects performed the required tasks with the DFS in the static (1g) mode. Then the subjects practiced under dynamic conditions in which the aeromodel G-levels were scaled and progressively increased as their skills improved up to a peak of +7.5 Gz.

The simulated bombing run consisted of a subject flying the aircraft to a predetermined waypoint, inverting at 10,000 ft, diving at +4 to +5 Gz, rolling upright and releasing a bomb at 8,000 ft AGL at ground SAM sites. Then the subject executed a high +Gz pull up such that the aircraft descended no lower than 5,000 ft AGL and flew outbound to the next waypoint marker. Subjects then performed a +4 Gz turn and returned

to the airport to deliver more ordnance on the SAMs. This pattern was flown continuously for one hour, completing up to nineteen passes to hit nine targets. Subjects' subjective fatigue levels were recorded after each bombing run and analyses of the changes in EMG and flight performance were concentrated on the bombing run, since this phase of the scenario was considered the most physically taxing. Performance ratings were based on the number of targets hit, the ability to meet altitude marks and the ability to sustain consistent G-loads during the pull-out.

A high-G multiple turn task (scaled for a +9 Gz aircraft) simulated a SAM avoidance type scenario. Subjects performed a series of level turns at a different altitudes which provided the same overall G exposure as recorded during an Operation Desert Storm incident which involved a pilot evading multiple SAMs. The sequence consisted of a 4 s +7.2 Gz left turn at 10,000 ft AGL (80% of maximum load of a +9 Gz aircraft), then a 10 s descent to 9,000 ft AGL, followed by a 4 s +3.6 Gz right turn (40% of maximum load), then a 10 s ascent to 11,000 ft AGL, followed by a 4 s +5.4 Gz right turn (60% of maximum load), then a 10 s descent to 10,000 ft AGL, at which point the sequence was repeated. Overall, 24 sets of three turns were completed in about 45 min.

SAM avoidance flight performance was assessed based on a weighted grading scheme. Two key parameters graded were the ability to maintain desired acceleration load (50% of grade) and altitude (50% of grade). Points were awarded based on how smoothly subjects controlled these parameters, i.e., holding G level and altitude with a minimum of oscillations. This was determined by calculating (1) the mean sum of squared errors (Mean SSSE) and (2) the r^2 correlation value with respect to the time of the turn (4 s). If the oscillations were effectively damped, then Mean SSSE should be minimal and r^2 should approach 1.0. To gauge the quality of the turn for G-load, time spent in the "good" range (7.2 ± 0.3 ; 5.4 ± 0.2 ; 3.6 ± 0.1 Gz), in the "fair" range (7.2 ± 0.5 ; 5.4 ± 0.3 ; 3.6 ± 0.2 Gz), sum of squared errors between target G-load and actual G-load and the r^2 correlation value between target G-load and actual G-load were calculated. To quantify subjects' ability to hold desired altitude, time spent in the "good" range (target ± 50 ft), in the "fair" range (target ± 75 ft), sum of squared errors between target altitude and actual altitude, the r^2 correlation value between target altitude and actual altitude, and if they reached the target altitude (± 100 ft) within 10 s to begin the turn were calculated. To determine the weight of the SSSE values, an average over the entire series of turns for a given G-load and subject was calculated and points were awarded for how close an individual turn was to that overall mean.

To simulate the muscular effort required to control an aircraft under asymmetric flight conditions (the emergency engine-out scenario), a pilot must apply constant back pressure on the control stick while partially deploying the rudders. To model this effort, the subjects first performed an ILS (Instrument Landing System) task with the control stick in the normal mode and the right rudder pedal partially depressed (between 1/3 to 2/3 fully depressed) as an experimental control. Then the control stick was modified so that to maintain trim the subject had to apply constant back pressure on the stick (equivalent to a +3 Gz pull). Then subjects performed an ILS task, waved-off and flew an oval pattern for approximately twenty minutes, and finished by repeating the landing task. Performance and muscular fatigue assessment were based on the difference between the first ILS compared to the second ILS task. The relative magnitude of the level of muscular effort required by the task was determined by comparing subject performance between landing with the stick in the control mode versus the loaded stick.

Engine out scenario flight performance was assessed similarly to the SAM Avoidance task. The task gauged subjects' ability to (1) maintain target altitude (16 points), airspeed (16 points) and heading (16 points) during the approach to the ILS glide slope intercept (APP); (2) maintain required airspeed (16 points), heading (16 points), and glide slope angle (16 points) while following the glide slope to the airport (GS); and (3) wave off above the minimum altitude (150 ft, 4 points). To determine the subjects' ability to maintain controlled flight during APP, the mean sum of squared errors and (2) r^2 correlation value with respect to time of approach for altitude, airspeed, and heading were calculated. To gauge quality of approach, time spent in the "good" range (1700 ± 50 ft; 170 ± 5 knots; $0 \pm 1^\circ$), in the "fair" range (1700 ± 75 ft; 170 ± 10 knots; $0 \pm 2^\circ$), sum of squared errors between target parameter and actual parameter and the r^2 correlation value between target parameter and actual parameter were calculated. To determine subjects' ability to maintain controlled flight during GS, the mean sum of squared errors and (2) r^2 correlation value

with respect to time of approach for airspeed, heading (horizontal deviation), and glide slope angle (GSA, vertical deviation) were calculated. To gauge quality of performance, time spent in the good range (170 ± 5 knots; heading: $0 \pm 1^\circ$; GSA: $0 \pm 0.25^\circ$), in the fair range (170 ± 10 KCAS; heading: $0 \pm 2^\circ$; GSA: $0 \pm 0.50^\circ$, respectively), sum of squared errors between target parameter and actual parameter and the r^2 correlation value between target parameter and actual parameter were calculated. To determine the weight of the SSSF values, an average of values for APP (and GS) for both days runs for a given subject was calculated and points awarded for how close performance of an individual task was to that overall mean.

Test	G-load	Muscle groups	Test variables	Performance variables
Static Ejection	+1 Gz	BM, BRM, TM, DM	EMG RMS, EMG f_{med} , HR, pull force, grip	
Open Loop Ejection	+3 Gz, +5 Gz, -1 Gz, -1.5 Gz, +1 Gx, -3 Gx, -5 Gx, ± 1 Gy	BM, BRM, TM, DM	EMG RMS, EMG f_{med} , HR, pull force, grip, subjective effort	
Dynamic Ejection	+1.4 Gz	BM, BRM, TM, DM	EMG RMS, EMG f_{med} , HR, pull force, grip	Time to ejection
Added Head Weight	-1 Gz, ± 1 Gy, ± 2 Gx, ± 4 Gx, +2 Gz, +4 Gz, SACM	SCM, TZM	EMG RMS, EMG f_{med} , HR, helmet weight, subjective effort	Identify targets and read displays
Bombing Simulation	Up to +7.5 Gz	BM, BRM, TM, DM	EMG RMS, EMG f_{med} , HR, subjective fatigue	Kill rate, consistency of G-load pulled, weapons release altitude, minimum altitude
SAM Avoidance Simulation	Repeated 10s +7.2 Gz, 10s +3.6 Gz, 10s +5.4 Gz	BM, BRM, TM, DM	EMG RMS, EMG f_{med} , HR, subjective fatigue	Maintain target G-load and altitude and controlled flight
Single Engine Failure Simulation	Up to +2 Gz	BM, BRM, TM, DM	EMG RMS, EMG f_{med} , HR, subjective fatigue, control stick load	Maintain airspeed, altitude, heading and controllability during landing approach and glide slope

Table 1. Summary of test conditions and physiologic, performance and test variables.

RESULTS

A summary of test results is given in Table 2.

Static Ejection

All six small stature female subjects were capable of meeting the requirement of 40 lb. pull forces with both the two hand (2-H) and one hand (1-H) grips. Mean ± 1 SD values for the peak pull forces (lb.) were: 2-H: 67.8 ± 0.9 (range 66.2 to 69.1); 1-H: 62.2 ± 6.0 (range 51.8 to 68.4). Subjects were able to pull a significantly higher force ($p=0.008$) with slightly less effort with the two handed (2-H) grip as compared with the one-hand (1-H) grip. Inflating the anti-G suit to 3 psi had no significant impact on subject ability to eject for any of the three grips based on the results of a two tail t-test. Subjects relied primarily on their biceps (BM) and to a lesser degree the brachioradialis (BRM) muscle groups during the 2-H and 1-H pulls.

Open Loop Ejection

All small stature female subjects could exert the required 40 lb. pull force using the 2-H grip under all conditions used to simulate ejection under adverse conditions. Using the 1-H grip, these subjects had a 93.8% success rate exerting a 40 lb. pull (one failed during -3 Gx (10.0 lb.) and another during -5 Gx (14.8 lb.) and +5 Gz (13.9 lb.) runs). Based on ANOVA results, there were no significant differences based on type of grip, but G-load had a significant effect on ΔHR ($F=8.55$, $p<0.001$). The largest ΔHR occurred during -3 Gx (16.0 ± 5.9 bpm), -5 Gx (18.9 ± 7.6 bpm), +3 Gz (27.5 ± 17.4 bpm), and +5 Gz (28.9 ± 17.1 bpm) and the smallest during 1.5 Gz (-0.5 ± 14.7 bpm) and +1 Gx (2.5 ± 5.8 bpm).

Based the mean normalized EMG RMS values, subjects relied primarily on their biceps and least on their triceps to perform these exertions. The second highest EMG activity was recorded from the deltoid muscles for the 2-H grip during most G-loads and from the BRM when using the 1-H grip (during -5 Gx, ± 1 Gy, -1.5 Gz, and +5 Gz exposures). A repeated measures ANOVA with a F-LSD post hoc test was conducted on the muscular effort exerted between the different grips used during static vs. dynamic conditions in order to determine whether the pull force itself caused subjects to rely more heavily on one muscle group as opposed to another. Few statistically significant differences based on G-load were found, and these were based on a marginally greater contribution from the triceps muscles during static runs compared with +1 Gx and -5 Gx runs.

Dynamic Ejection

Five small stature subjects participated in this portion of the investigation. These subjects successfully navigated the route and ejected without crashing using both grips. There were no statistically significant differences in measured muscular effort when comparing the 2-H to the 1-H grip during performance of the dynamic ejection tasks. However, based on a two tailed t-test, it took significantly less time ($p = 0.03$) to execute a successful ejection using a 2-H grip (0.28 ± 0.13 s) compared with the 1-H grip (0.62 ± 0.41 s). Note that during dynamic runs, subjects seemed to rely on the BRM muscle group to a greater extent than the BM when compared to the static or open loop ejections. Since this maneuver was conducted at low +Gz (≈ 1.4 Gz), a repeated measures ANOVA test was conducted between static and dynamic ejection normalized EMG RMS values. For both 2-H and 1-H grips, subjects exerted significantly greater effort during the dynamic ejection sequence with the BRM (2-H: $F=34.44$, $p<0.001$; 1-H: $F=5.06$, $p = 0.046$) and the TM (2-H: $F=35.89$, $p<0.001$; 1-H: $F=29.05$, $p<0.001$) muscle groups compared with the static runs.

Added Head Weight

All subjects could read all displays while supporting up to 5 lb. during -1 Gz, ± 1 Gy and up to 16 Gz (SACM) exposures. Subjects often had to move their mask and/or mask hose to view the lower displays and the control stick interfered with line of sight during some G exposures (particularly Gx and Gy). Subjects wearing the standard configuration (3.5 lb.) reported difficulty during +4 Gx (the smallest subjects had trouble reading lower displays) and -4 Gx runs (two subjects could not lift their heads, two could only read the bottom half of the HUD and one misread the altitude and heading). The same problems persisted while wearing the 4.25 lb. helmet. It was difficult to impossible for subjects to read lower displays under +4 Gx or keep their heads upright during the -4 Gx conditions while supporting 5 lb.

There were no statistically significant differences found in normalized SCM or TZM EMG RMS based on helmet weight or head position except (1) increasing head weight from 4.25 to 5.0 lb. was associated with a significant rise in SCM EMG RMS during the -4 Gx runs ($F=4.46$, $p=0.045$) and (2) the same increase led to a decrease in TZM EMG RMS during the SACM runs ($F=3.48$, $p=0.047$). Overall, the normalized EMG RMS magnitude of TZM was larger when subjects looked down compared with the head up position. However, subjects exerted greater effort with the flexor muscles (SCM) when they looked up compared with looking down. It required a greater contribution from the TZM group than the SCM for subjects to hold their heads in the midrange position for all G-loads except those in the Gz plane.

Bombing Simulation

Three subjects participated in the bombing simulation. The subject pool recorded an overall 70.3% kill rate of ground targets. While significant differences in RMS and f_{med} between the three subjects were found, no statistically significant difference in RMS or f_{med} based on run order was demonstrated. Therefore, individual subject effort appeared to be consistent throughout each insertion.

Level of G's pulled was also consistent. The variation in G-load ranged between ± 0.18 and ± 0.45 Gz. No statistically significant difference in G-load was demonstrated relative to run order ($F = 2.19$, $p = 0.086$), although subjects as a group tended to pull higher loads during later runs compared with early runs (on the order of $+0.5$ Gz). This may indicate increasing fatigue as subjects might have been losing the ability to produce a more graded effort on the control stick. No significant differences in the weapons release altitude between bombing runs were demonstrated. However, the minimum altitude reached during pull out was significantly lower at the end of the insertion compared with earlier runs ($F=5.11$, $p=0.002$). While this may be a function of increasing fatigue, subjects were still able to maintain their aircraft within the prescribed envelope. Only one subject reported subjective fatigue levels greater than moderate.

SAM Avoidance Simulation

Four small stature females participated in these exposures. One terminated her second insertion early, which she attributed to insufficient rest between insertions. Another completed her first series of turns but on her second attempt, completed only 17 sets (total of 51 turns) after displaying apparent Almost Loss of Consciousness (A-LOC) symptoms. She stopped flying, expressed feelings of confusion, shaking, and her hand made jerky involuntary motions until she noticed the symptoms and then it stopped. Some subjects reported arm discomfort as the task progressed. Based on results from repeated measures ANOVA tests, there were no statistically significant differences in performance grades based on run order (i.e. between early and later turn sequences) for each G-load.

For the EMG analyses during this simulation, the last set of completed turns of the two subjects who ended their second insertions prematurely were included with the last set of turns of the other subjects. During the $+7.2$ Gz turns, subjects exerted statistically significantly lower force during later turns compared with the earlier turns for the BRM ($F=2.79$, $p=0.040$) and the TM ($F=2.67$, $p=0.042$). Few statistically significant differences in effort were found during $+5.4$ or $+3.6$ Gz turns. There were also few statistically significant differences in Δf_{med} found based on the turn set number for $+3.6$ or $+7.2$ Gz turns. Overall for this group of subjects, Δf_{med} for BRM and BM decreased relative to unstressed levels while Δf_{med} were variable for TM and DM.

Single Engine Failure Simulation

Three subjects participated in the engine failure simulation. Flight performance was based on how well the subjects performed the ILS landing task. Results from the repeated measures ANOVA tests indicated that no statistically significant difference based on run order or stick load was found.

Two phases of the ILS task were selected to compute changes in EMG. These were (1) during straight and level flight during approach (APP) and (2) during the wave off procedure after following the glide slope toward the airport (WO). Due to technical problems, EMG recordings from all muscle groups could not be obtained. An analysis of the effort required during the unloaded versus loaded control stick condition indicated that during APP the EMG RMS values for BRM and BM were significantly greater during the loaded stick condition ($F=17.51$, $p=0.002$ and $F=11.82$, $p=0.009$, respectively). BRM and TM f_{med} during the loaded stick condition were significantly lower during the loaded stick condition as well ($F=44.76$, $p<0.001$ and $F=37.18$, $p<0.001$, respectively). At wave off, EMG RMS values for BRM and BM were also significantly greater during the loaded stick condition ($F=17.72$, $p=0.001$ and $F=8.54$, $p=0.019$, respectively) and the BRM and TM f_{med} during the loaded stick condition were also significantly lower than during the unloaded stick condition ($F=22.83$, $p=0.001$ and $F=41.76$, $p<0.001$, respectively). Therefore, piloting with the control stick in the loaded condition required a greater flexor muscle group effort than in

the control mode. Note that ANOVA results indicated that ΔHR was independent of the load condition of control stick during APP and WO.

EMG measurements taken during the first ILS task were compared with the second task with the control stick loaded. While BRM, BM, and TM EMG RMS values were greater during the second ILS task compared to the first, the increases were not statistically significant. During APP, there was a statistically significant decrease in BRM and TM f_{med} during the second ILS task compared with the first ($F=38.90$, $p=0.001$ and $F=51.58$, $p=0.002$, respectively). A similar pattern occurred during the WO phase in which the decrease in BRM and TM f_{med} was significant ($F=9.62$, $p=0.021$ and $F=41.43$, $p=0.003$, respectively). While each subject indicated that her subjective fatigue increased during the simulation, subjects described the increase in fatigue as slight to moderate and the decrease in f_{med} indicated that at least some of the fatigue was muscular in origin. When comparing ΔHR between the first and second APP or WO, ANOVA results indicate that the increase was statistically significant and may provide additional evidence of rising fatigue levels ($F=12.52$, $p=0.012$ and $F=8.01$, $p=0.03$, respectively).

Test	Performance	Primary muscle group	Statistical significant results
Static Ejection	Met 40 lb. goal with 2-H and 1-II grips	BM	2-H greater force than 1-H
Open Loop Ejection	Met 40 lb. goal with 2-H under all G-loads (three 1-H failures at +5 Gz, -3 Gx, -5 Gx)	BM	Greatest increase in HR during -Gx and +Gz runs
Dynamic Ejection	All successfully initiated ejection	BRM	2-II grip pull faster than 1-II; greater effort than static runs
Added Head Weight	Supported up to 5 lb. during -1 Gz, +1 Gy, +2 Gz, +4 Gz, SACM. Difficult to impossible during ± 4 Gx	Dependent upon head position	Greater SCM (lower TZM) effort supporting 5 lb. than 4.25 lb. during -4 Gx runs
Bombing Simulation	70% kill rate, consistent G-load pulled, ability to achieve altitude targets over time	No difference over time	Minimum altitude lower over time
SAM Avoidance Simulation	No difference in performance over time; 2 subjects terminated runs early (A-LOC and fatigue, respectively)	BM and BRM f_{med} decreased over time (increased fatigue)	BRM & TM effort decreased over time
Single Engine Failure Simulation	No difference in landing performance over time or control stick load condition	BM, BRM effort greater with loaded control stick	Loaded control stick associated with greater flexor muscle effort and BRM and TM fatigue; HR rose over time

Table 2. Summary of test results.

CONCLUSIONS:

Within the scope of these tests, small stature females demonstrated the strength and endurance to safely fly physically strenuous missions and safely initiate ejection during severe physically taxing dynamic conditions. However, cockpit accommodation and pilot reach limits may hinder the small stature pilot during flight emergencies requiring full stick authority or ejection during flat spin and arrestment. Additionally, some small stature female pilots may not be able to properly position their heads due to a combination of inadequate restraint and lack of sufficient neck strength to read critical displays during flat spin recovery conditions and arrestment.

Given that the results from the ejection studies indicate that these test subjects had superior performance using the 2-H grip, it is recommended that when training small stature individuals, emphasis should be placed on this grip. While criteria for a successful ejection in this report was based on the ability to exert a 40 lb. force applied to the actuator, in many circumstances, the small stature female subjects marginally met this criteria. It should also be noted that this exertion level is lower than several other ejection seats currently being flown. Escape system actuation will be a larger problem with small stature females in other aircraft escape systems.

The significant difference in EMG measurements between performance during static vs. dynamic ejection simulations emphasizes the utility of adding motion cues and a performance incentive (i.e. avoiding crashing). Dynamic simulations produce significantly different behavior compared with static simulations and must be included for appropriate interpretation of results and generalization to operational settings. This result emphasizes the limited utility of using static strength measurements when predicting performance of tasks requiring dynamic muscular exertions.

No indications of muscular fatigue were found during the added head weight exposures (up to 20 sec). After the tests, some subjects reported headaches and hip discomfort (from lap restraints), but no neck pain. Objective measures of increased muscle fatigue based on changes in median EMG frequency were not demonstrated. While no neck pain was reported, these tests were conducted with carefully weighted helmets and subjects limited their head motion under G. These results may not be the case for helmet mounted displays in which the center of gravity is pitched forward. Therefore, it would not be advisable to directly apply these results to the prediction of potential injury associated with neck pain as a result of head motion during aerial combat or ejection related injuries.

The most physically taxing flight simulation was the SAM avoidance task. This was the only task in which A-LOC symptoms were reported and subjects complained of arm pain. Despite the arduous nature of the task, statistical analysis of flight performance indicated no significant decline in subjects' ability to fly. For the highest G-load (+7.2 Gz), subjects exerted a statistically significantly lower amount of force during later turns compared with the earlier turns for the BRM and the TM muscle groups. Based on EMG analysis, there was no linear increase in muscle fatigue indicators and subjects did not demonstrate a need for consistent increases in muscular effort to maintain control over time.

Performance and effort was consistent during the bombing simulation with subjects achieving an overall 70% kill rate of ground targets. Subjective fatigue ratings were "very low" for two of the three subjects. No statistically significant increase in muscular fatigue was found during each simulation run.

Based on their ability to execute an ILS landing, performance scores were not significantly different between the first maneuver and after 20 minutes of flying during the simulated single engine failure task. While the level of muscular effort did not significantly change over time, decreases in EMG frequency content indicated that there was an increase in BRM and TM muscular fatigue. Increases in heart rate over time also implied an increase in fatigue even though subjective assessments of fatigue were rated "moderate" at most.

Even though there were indications of changes in muscle effort and fatigue as the performance time of the various flight tasks increased, no significant decrements in performance were demonstrated. However, interpretation of the results presented in this report must be tempered with the knowledge that all subjects did not participate in all phases of the experiments. Even though a repeated measures design was used, statistical results should be interpreted as only an indication of how small stature females could perform in these situations. A larger sample of subjects would increase the statistical power of these results. Deficiencies in muscular strength and endurance identified in this investigation may be overcome by suitable training in a motivated population. However, the grit and integrity that these subjects displayed is not sufficient to overcome the reach limitations which could limit their effectiveness in emergency situations. Accommodations in the areas of reach and clothing fit are essential to support the inclusion of this portion of the population in the high performance aircraft arena.

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